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Wind Effect on Vibration and Scattering Behavior of Japanese Roofing Tile

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Abstract

A series of wind tunnel tests were conducted on the vibration and scattering behavior of full-size models of tiles widely used as roofing materials on Japanese wooden dwellings. This study has investigated the nature and source of such movement with the aim of providing better insight into the mechanism. The result of these measurements indicates that a basic mechanism can be developed that will lead to flow-induced vibration of the roofing tiles. The values of the oscillation frequencies relate to the values of natural frequencies of the vibration.

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Keywords: Wind Tunnel Tests, Roofing Tile, Flow Visualization, Flow-induced Vibrations, High-speed Video Camera

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1. Introduction

The wind load on a roofing element is created by the difference in the external and internal pressure. The net wind load is generally determined by the building flow field, wind gustiness, and element flow field [1], [2]. While these parameters directly influence the external pressure distribution on the roofing element, the

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internal pressure development, depending indirectly on these parameters, is governed by a dynamic response that varies in the roofing elements. The pressure distribution on the external roof surface and the internal pressure are well known from previous investigations [3], [4]. The element wind load may differ significantly from the load derived by the external pressure distribution. The internal pressure is governed by the wind permeability of the surface, which is determined by openings such as gaps between tiles and venting devices as well as the resistance from equilibrating flow through and underneath the wind permeable surface [5].

Flow-induced vibration of roofing tiles generally appears immediately before their scattering. The flow-induced vibration (aeroelastic instability) of structures is an important phenomenon for the following two reasons: (1) Strong lateral, self-excited oscillations can develop at a certain wind velocity (onset velocity) as a result of the lateral aerodynamic force component, and (2) the tendency to these vibrations affects the behavior of the structure below the onset velocity as it produces a negative aerodynamic damping, which can considerably reduce the total damping available to the structure [6]. The investigation of flow-induced vibration of roofing tiles prior to the scattering has attracted little attention. This study investigates the nature and source of the vibration and scattering behavior of these tiles with the aim of providing a clearer insight into the mechanism, and this paper presents the initial results of studies into the wind-inducing device for the tiles.

Using wind tunnel tests, a study was conducted to clarify the behavior of the roofing tile vibration and the primary factors that affect the scattering. The results indicate that the vibration mechanism behaves in a manner consistent with that of a self-excited system, and the surface flow creates reasonable uplifting moments only for wind directions roughly perpendicular to the eaves.

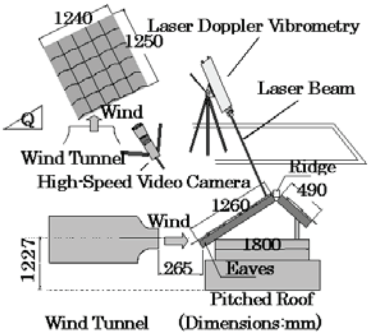
Nomenclature

P	pitch angle
Q	flow angle
U	upstream flow velocity
X	streamwise coordinate
Y	transverse coordinate
Z	perpendicular coordinate to surface of roofing tile

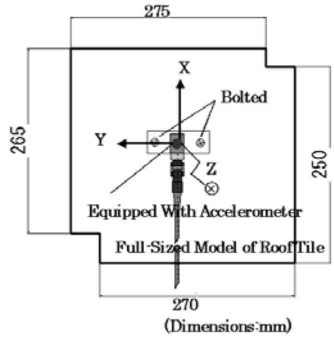
2. Test Facility and Analysis Procedure

The schematic diagram in Fig. 1 illustrates the general layout of the test facility used in this investigation. The experiments were conducted in an open-circuit wind tunnel that was driven by an axial-flow fan. The nozzle of the wind tunnel had a 500 mm × 1,300 mm cross section. The maximum velocity of flow from the nozzle was about 50.0 m/s. The streamwise turbulence intensity of the flow was about 10% of that generated by the grids. The turbulence intensity of the flow condition is in the same order as the turbulence intensity of approached wind flow experienced in practice.

Twenty-five roofing tiles were set up in five lines by five rows on a pitched roof in the downstream flow from the wind tunnel (Fig. 1 (a)). The roofing tiles were composed of clay, and each weighed about 2.8 kg. The vibrations of the roofing tiles were measured by a Laser Doppler Vibrometry (LDV, OMETRON VS1000) and an accelerometer (ONO SOKKI NP-3560), and the practical natural frequencies of the roofing tiles were analyzed by the impulse force hammer test method. The vibration velocity could be measured up to 1,000 mm/s by the 1 mW LDV, and the vibration frequency range was from dc to 50 kHz. Each roofing tile was equipped with an accelerometer, as shown in Fig. 1 (b). The accelerometer was used to measure the dynamic behavior in three directions; X, Y, and Z axis of tiles; and weighed about 5.0 g. The experiment to measure vibration frequencies of the tiles was generally performed by the accelerometer. Unfortunately, the vibration frequencies identified by the LDV were limited to small amplitude modes. In this study, the accelerometer method and the LDV technique were employed to determine the resonant frequencies of the tiles both bolted and unbolted to the roof bed.



(a) Wind tunnel and tiled roof



(b) Roofing tile equipped with accelerometer

Fig. 1. Experimental apparatus

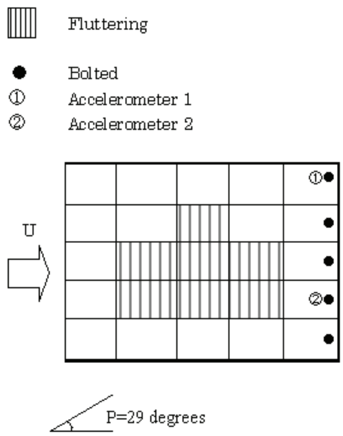
The dynamic instability of the structures under excitation was also investigated by the visualization method. The motions of the vibration with the large amplitude and the scattering of roofing tiles were observed by a high-speed video camera (PHOTRON FASTCAM-PCI 2KC). The camera acquired 2,000 frames per second, and the acquired images had 512 × 480 pixels on each full frame. On the other hand, a hot-wire anemometer and a linearizer were used to measure the turbulence intensity of the surface flow over the roofing tiles.

3. Results and Discussions

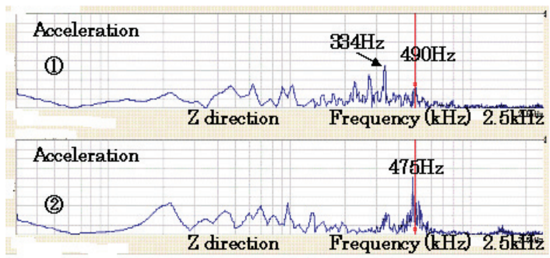
3.1. Acceleration power spectrum for roofing tiles

Examples of vibration and scattering behavior of roofing tiles and vibration frequencies measured by two accelerometers (Accelerometer 1, 2) are illustrated in Fig. 2. The critical areas, the vibration and scattering tiles, are indicated in Fig. 2 (a). Figure 2 (b) clearly shows a narrow-band peak in the vibration spectrum that increases gradually in amplitude as the wind velocity is increased. These characteristics are typical of vibrations and are consistent with observations under the geometries with which bolts were connected. Figure 2 (b) also shows the vibration resonance to be excited at a frequency nearly consistent with that of the natural vibration, and these vibrations seem to appear generally in a direction perpendicular to the surface of the tiles.

The difference between the geometries with which bolts were or were not connected in the damping of the vibration response was investigated using the technique described in the Test Facility and Analysis Procedure for roofing tiles with differing geometries. These measurements were performed for a series of velocities up to the onset velocity of the scattering behavior of the full-size model of roofing tiles. These results show that the frequencies of the vibration remain fairly constant as the wind velocity increases; however, as the wind velocity approaches the onset velocity, a sharp increase in the peak of the frequency spectrum occurs. Figure 2 (b) shows that the vibration resonance was increased through the full velocity range available, and only a large peak of 475 Hz in Accelerometer 2 is evident at the very limit of the velocity range. This type of result was obtained in all the experimental conditions investigated and suggests that the vibration system is self-excited. The vibration system is stable under no-flow conditions. Then, as a result of interaction between the vibrations and the flow, it is suggested that the vibration system becomes unstable and leads finally to roofing-tile scatter.



(a) Vibration and scattering behavior of roofing tiles



(b) Vibration frequencies measured by two accelerometers

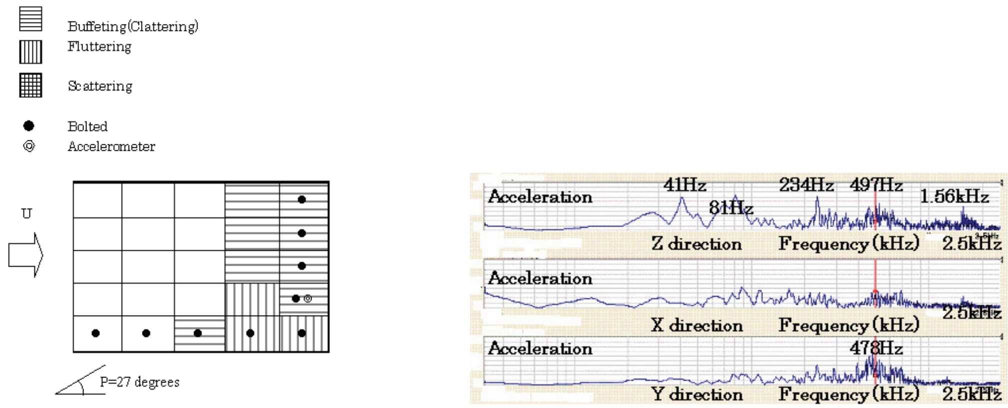
Fig. 2. Vibrational acceleration power spectrum for roofing tiles for P = 29 degrees, Q = 0 degrees and U = 39.0 m/s

It is clear that the amplitudes with the resonant frequencies of the roofing tile are amplified as the flow velocity increases. However, it was difficult to measure the resonant frequencies in the dynamic behavior of the roofing tile by using LDV because the intensity of laser beam reflection from the surface of the tiles became weaker for large amplitude of the vibration. On the basis of the measurement results, we notice that there is a basic mechanism that will lead to flow-induced vibrations of the roofing tiles. This mechanism is similar to that of fluttering instability, which appears as the self-excited oscillation in the natural mode of the structure at certain critical speed. The values of the frequencies for the oscillation relate to the values of natural frequencies of the vibration. This investigation makes a strong point toward revealing a complex mechanism that cannot be satisfactorily explained by the fluttering model. It has also been shown that the vibration mechanism behaves in a manner consistent with that of a self-excited system.

3.2. Vibration and scattering behavior of roofing tiles

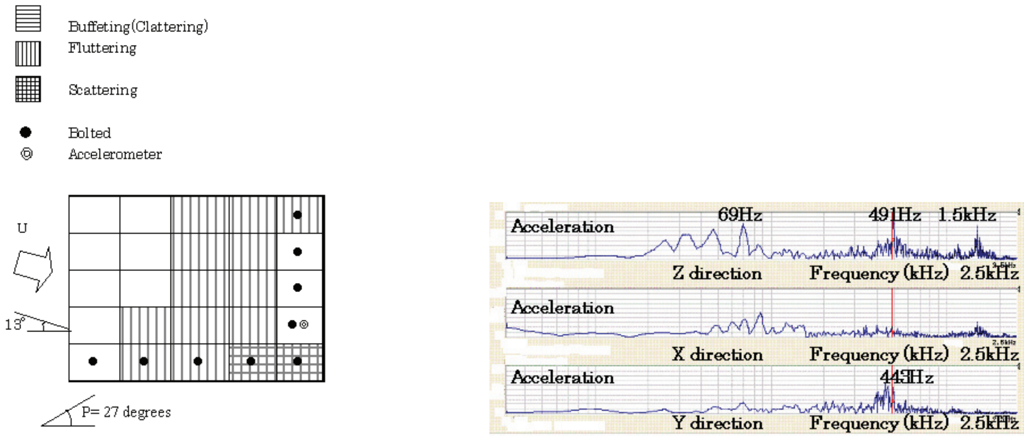
The wind load on a roofing tile is determined by the difference in the external and internal pressure. The external pressure distribution depends on the flow field around the building and on the local flow because of the outer shape of the surface element. The internal pressure is governed by the wind permeability of the surface, which is determined by openings such as gaps between tiles and venting devices as well as the resistance for the equilibrating flow through and underneath the wind permeable surface [7].

Wind load on tiles for various pitched roofs and different flow directions were measured in wind tunnel tests. For pitch angle P = 27 degrees and flow angle Q = 0 degrees, similar to wind direction perpendicular to the ridge, the typical result is shown in Fig. 3. In Fig. 3 (a), the bold dots show the bolted tiles, and the double circle shows the position of the accelerometer. The lateral striped areas show the clattering or buffeting tiles. The vertical striped areas show the fluttering type of tiles. Figure 3 (b) shows the vibrational acceleration power spectrum in Z, X, and Y direction, respectively. The critical external pressure distribution occurs only for flow directions more or less perpendicular to the ridge [4]. To hoist the tiles, the local velocities must be relatively high, corresponding to a stagnation pressure. Fortunately, such high local velocities for this critical direction occurred only in relatively small areas of the roof. The size and position of these critical areas depend on the pitch angle. The critical areas as well as the vibrating and scattering tiles are indicated in Fig. 3 (a). For areas having a wind-exposed roof, nails or clamps should be used to secure the tiles.



(a) Vibration and scattering behavior of roofing tiles (b) Vibration frequencies measured by two accelerometers

Fig. 3. Vibrational acceleration power spectrum for roofing tiles for P = 27 degrees, Q = 0 degrees and U = 39.0 m/s



(a) Vibration and scattering behavior of roofing tiles (b) Vibration frequencies measured by two accelerometers

Fig. 4. Vibrational acceleration power spectrum for roofing tiles for P = 27 degrees, Q = 13 degrees and U = 40.0 m/s

Figure 4 shows the results for P = 27 degrees and Q = 13 degrees. The vertical striped areas show the fluttering type of tiles, and cross-striped areas show the scattering tiles in Fig. 4 (a). The onset velocity of the scattering of roofing tiles is 40 m/s. Figure 4 (b) shows the vibrational acceleration power spectrum in Z direction, X direction, and Y direction, respectively.

Reference [8] described the lifting mechanism of a tile by a moment that turns the tile upward around the pivoting point on the batten. The moment consists of a lifting force and two force couples caused by the external and internal pressure distribution, respectively. Figure 5 shows the excerpts of a high-speed video camera image that demonstrates this lifting mechanism for wind direction perpendicular to the eave. For local flow direction perpendicular to the ridge, the internal pressure in the space between tiles and underlay may become positive because of the stagnation, and the net wind load is increased by the sealing effect of the underlay. However, the pressure equilibration in the gable room is prevented, leading to a much lower net wind load for the leeward roofing tiles. Aerodynamically favorable tiles should have shapes that avoid stagnation at the overlaps. The permeability at the overlapping gaps parallel to the ridge should be small, and the permeability at the interlocking gaps perpendicular to the ridge, where suction due to the element flow field occurs, should be high [3].

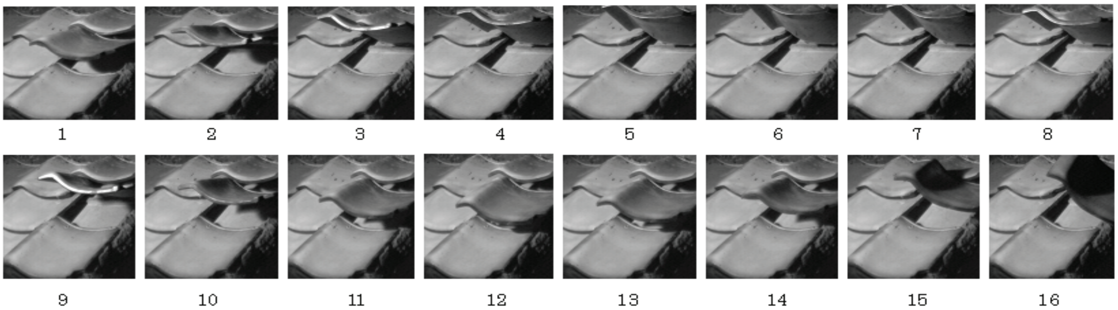


Fig. 5. High-speed video camera image of roofing tile lift due to wind action at time intervals of 0.01 seconds

4. Conclusions

An experimental study was conducted by using wind tunnel tests to clarify the behavior of roofing tile vibration and the primary factors that affect the scattering. The results are summarized as follows:

1. The roofing tile vibration amplitude increases rapidly at certain critical wind speed.
2. The basic mechanism that can lead to the flow-induced vibrations of the roofing tiles is similar to that of fluttering instability, which appears as self-excited oscillation in the natural mode of the structure at certain critical flow speed. The values of the frequencies for the oscillation relate to the values of natural frequencies of the vibration.
3. The surface flow is important only on the windward side of the roof and creates reasonable uplifting moment only for wind directions roughly perpendicular to the eaves.

5. Acknowledgment

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